Developmental Testbed Center (DTC) Project for the Hurricane Forecast Improvement Program (HFIP)

Final report documenting:

Regional Application of the GSI-Hybrid Data Assimilation for Tropical Storm forecasts - Tackling the intensity spin down in 2014 HWRF runs

September 2015

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1. Introduction

This report covers the work conducted at the Developmental Testbed Center (DTC) in FY14 on the regional application of the GSI (Gridpoint Statistical Interpolation)-Hybrid variational-ensemble data assimilation for the tropical storm forecast, mainly focusing on the intensity spin-down at the initial hours in the 2014 HWRF (Weather Research and Forecast model for Hurricane) system.

The intensity spin down was first discovered in the 2014 HWRF pre-implementation runs, with the storm intensity bias decreasing rapidly in the first few hours. Figure 1 shows the plots from Ryan Torn at State University of New York at Albany, who examined the tropical cyclone biases in 2013 and 2014 HWRF runs. The figure presents the aggregated intensity biases from the retrospective runs for the years 2010-2013 for both Atlantic Basin (left) and the East Pacific Basin (right). The black curves are from 2013 HWRF runs and the red curves are from the 2014 HWRF runs, with solid lines representing weak storms (initial intensity less than 70 knots for the Atlantic Basin and less than 65 knots for the East Pacific Basin) and dashed lines representing strong storms (initial intensity more than 70 knots for the Atlantic Basin and more than 65 knots for the East Pacific Basin). Comparing the red dashed line (2014 HWRF, strong storms) and the black dash line (2013 HWRF, strong storms) reveals that the 2014 HWRF runs produce positive intensity bias at 00 hour for both the Atlantic and East Pacific basins, and shortly after, the positive biases altered to negative biases. The sudden decreases of the intensity biases are ~10 knots for the Atlantic and ~12 knots for the East Pacific in the first 12 hours. However, this sharp decrease of the intensity bias is not significant in the 2013 HWRF runs.

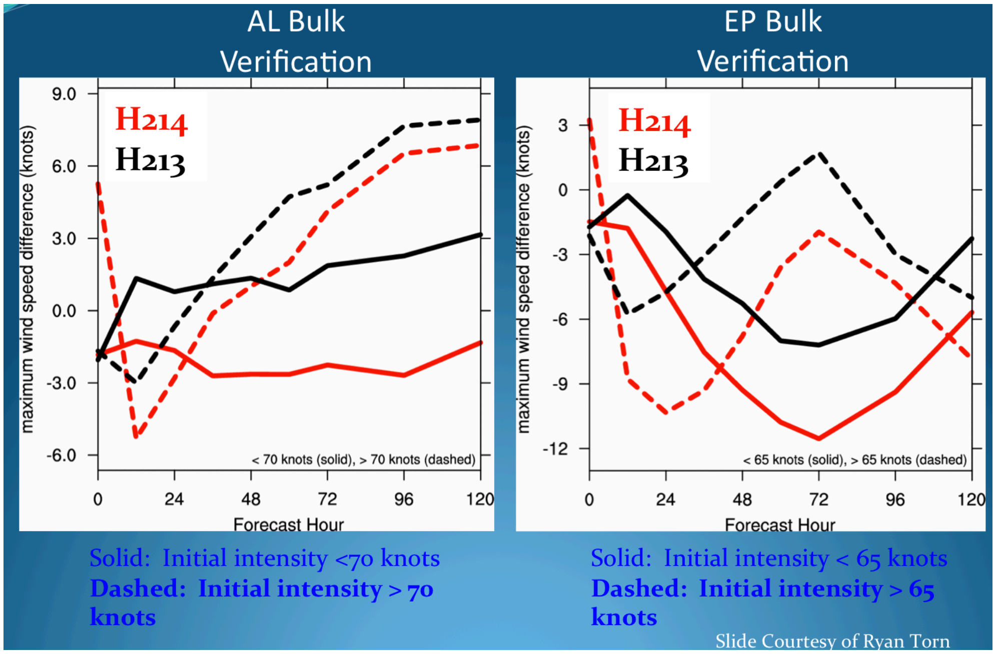

Figure 1. Intensity biases of the 2013 (black) and 2014 (red) HWRF runs for the storms in the years 2010-2013, for the Atlantic (left) and the East Pacific (right). Solid lines represent weak storms (initial intensity less than 70 knots for Atlantic basin and 65 knots for the East Pacific basin) and dashed lines represent strong storms (initial intensity more than 70 knots for Atlantic basin and 65 knots for the East Pacific basin). Adopted from the slide by Ryan Torn.

The intensity spin-down in 2014 HWRF runs was also confirmed at the DTC through examining the aggregated errors of the 2014 HWRF pre-implementation runs for the years 2010-2013, archived at NCEP (National Centers for Environmental Prediction) EMC (Environmental Modeling Center). Figure 2 gives the DTC plots of the aggregated intensity biases for the strong storms at the Atlantic (left) and the East Pacific (right) basins, confirming the findings by Ryan Torn. This leads to the main topic of this study, that is, what are the possible causes for the intensity spin down in the 2014 HWRF system?

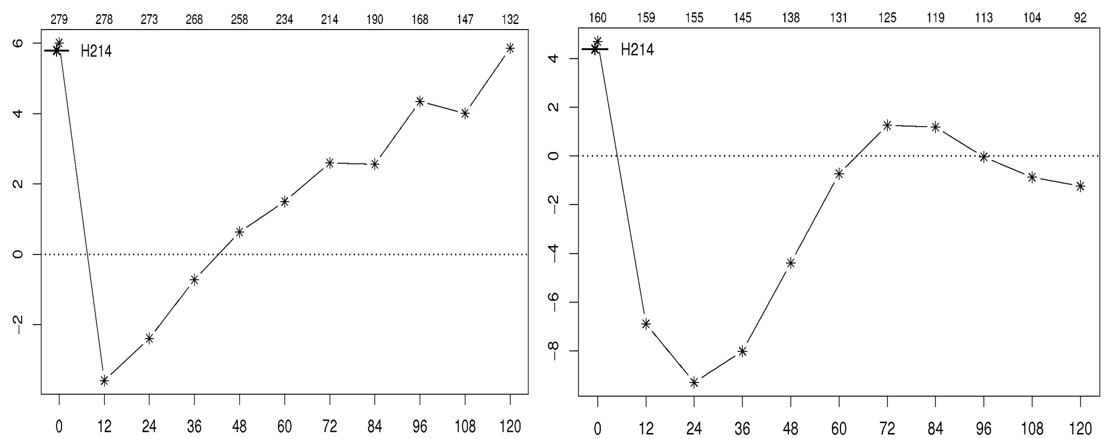

Figure 2 Intensity biases of the strong storms in the 2014 HWRF pre-implemental runs in the years 2010-2013, for the Atlantic (left) and the East Pacific (right). Strong storms correspond to the storms with initial intensity of more than 70 knots for Atlantic basin and 65 knots for the East Pacific basin. The numbers of cases are shown on top of the plots. The X-axis corresponds to the forecast lead times (0-120 hours).

Section 2 of this report will introduce the system used in this work. In section 3 test cases will be selected, while section 4 will cover the multiple experiments conducted to examine the causes of the intensity spin down and efforts to remove or mitigate the sharp decease of the intensity bias. Section 5 discusses the findings in section 4, with possible solutions and potential problems within the system.

2. Model configuration

As discussed in the above section, the intensity spin down happened in the 2014 HWRF pre-implementation runs. To further examine the causes of the spin down, a model system is needed and this system should be able to replicate the issue. The 2014 version of the HWRF operational system, checked out from the HWRF repository in late June of 2014, is used in this study. The atmospheric part of the system is the Non-hydrostatic Mesoscale Model (NMM) dynamic core of the WRF model (WRF-NMM), which has a parent domain (75°x75°, 0.18° (~27km) horizontal resolution) and two nest domains (0.06° (~9km) and 0.02° (~3km) horizontal resolution). Figure 3 gives the HWRF data assimilation and model forecast domains, in which ghost_d02 and ghost_d03 are the two domains for the GSI hybrid data assimilation. Vortex initialization, as part of the model initialization, is performed before the data assimilation and provides the background fields for the data assimilation.

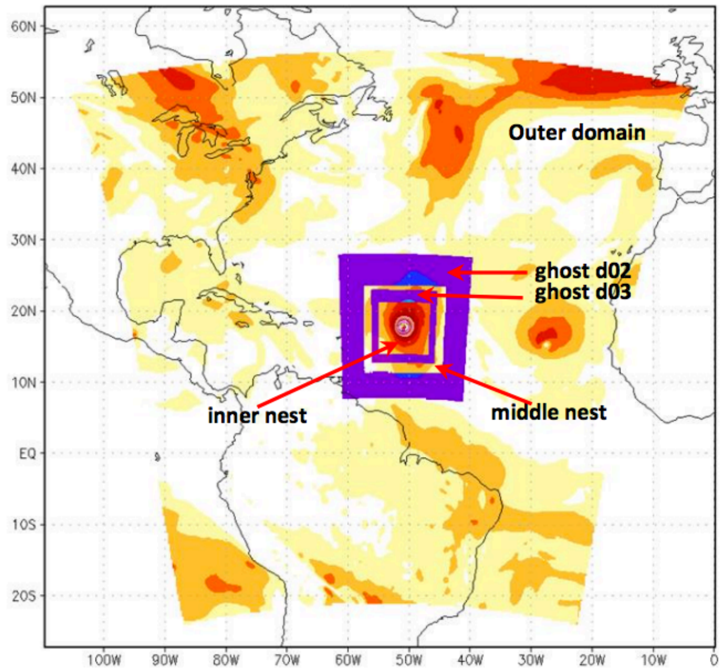

Figure 3. HWRF data assimilation and model forecast domains. Adopted from the HWRF Scientific Document (http://www.dtcenter.org/HurrWRF/users/docs/scientific_documents/HWRFv3.6a_ScientificDoc.pdf)

Compared to 2013 HWRF, the updates in the 2014 HWRF include, but not limited to:

- Increased model levels from 43 to 61 levels.
- Raised model top to 2mb from 50mb.
- Upgraded vortex initialization scheme.
- Changes to the GSI hybrid data assimilation.

The two data assimilation domains changed from the parent and ghost_d03 for 2013 HWRF to ghost_d02 and ghost_d03 for the 2014 HWRF. Another major difference between 2013 and 2014 HWRF is the additional data assimilated in 2014 HWRF, including the satellite radiance, satellite winds and GPS (Global Positioning System) RO (Radio Occultation). More details are listed in Table 1, comparing the data assimilation configurations for the 2013 and 2014 HWRF. In both 2013 and 2014 HWRF runs, the 80-member 6 hour forecasts of the global ensemble are used in the GSI hybrid data assimilation to provide flow-dependent information, in addition to the static (3DVAR) background error covariance. The weights of the ensemble and static error covariance are also shown in the table below.

Table 1 Data assimilation configurations for the 2013 and 2014 HWRF

	D01 (27km)	**Ghost_d02 (9km)**	**Ghost_d03(3km)**
2014 HWRF	Using GFS analysis	20°x20°	10°x10°
		Conventional, satellite radiance, satellite wind, GPS RO, TDR	Conventional data and TDR
		80% ensemble; 20% 3DVAR	80% ensemble; 20% 3DVAR
2013 HWRF	Conventional data (including TC Vital)		20°x20°
	75% ensemble; 25% 3DVAR		Conventional data and TDR
			80% ensemble; 20% 3DVAR

The Unified Post-Processor (UPP) and GFDL (Geophysical Fluid Dynamics Laboratory) vortex tracker are also included in the HWRF system for post processing to produce GRIB format model output and generate the storm track and intensity forecast files in the ATCF (Automated Tropical Cyclone Forecasting) format. The Model Evaluation Tools for Tropical Cyclones (MET-TC) is then utilized to verify the tropical cyclone track and intensity forecasts against the observation – best track data, and make plots of the error statistics.

3. Case study

All the storms for the years 2010-2013 in the 2014 HWRF pre-implementation runs are verified against the best track data and plots are made based on the aggregated statistics for each individual storm. After careful examination, Irene (2011) stands out among all the storms for its strong signal of the intensity spin down and therefore is selected for this case study.

Irene is the ninth named storm of 2011 in the Atlantic. It started from a tropical wave at the west coast of Africa on August 15, 2011 and formed a tropical storm shortly before August 21 to the east of Martinique. While moving towards the west-northwest, Irene became a hurricane at around 06Z August 22 and became a category 3 hurricane at around 12Z August 24. It weakened a little bit after 00Z August 25 but still remained a hurricane until after 06Z August 28. Irene made landfall in North Carolina at 12Z August 27, 2011, causing widespread damage. Figure 4 is from the tropical cyclone report for Hurricane Irene by the National Hurricane Center (NHC) (http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf), depicting the full lifetime of the strength and path of Irene.

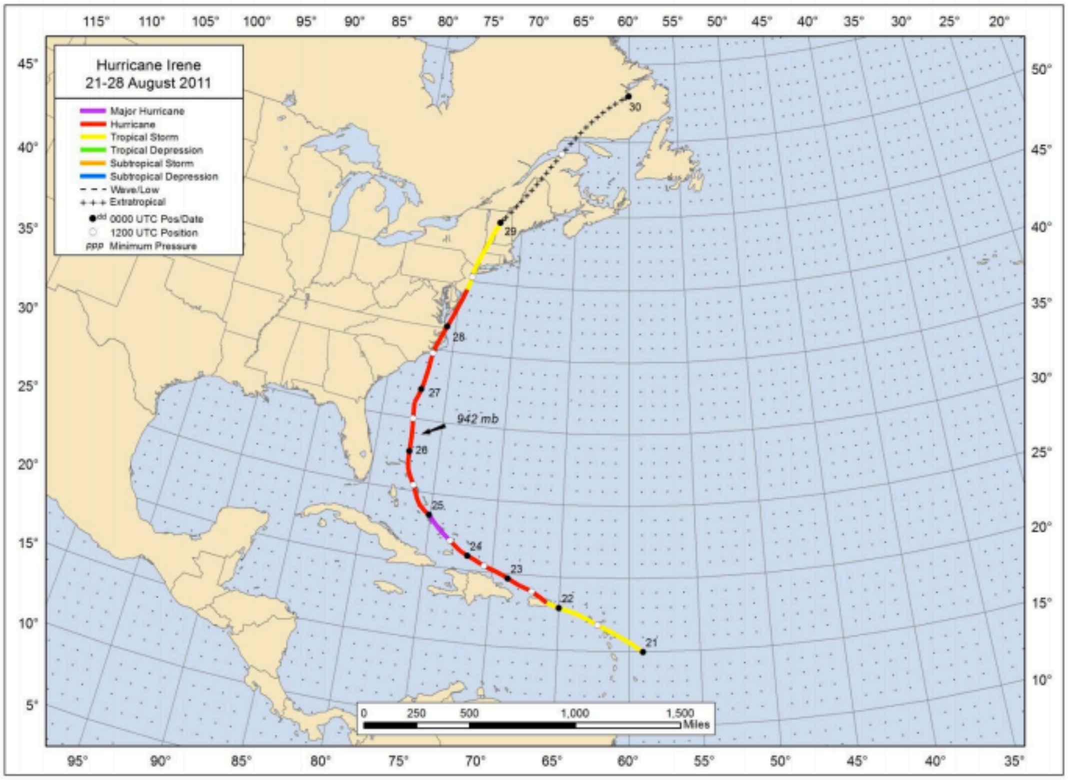

Figure 4. Best track positions for Hurricane Irene, 21-28 August 2011. Adopted from the tropical cyclone report for hurricane Irene by the NHC.

Before going ahead with in-depth investigations, we need make sure that the model system can reproduce the spin down issue that existed in the 2014 HWRF pre-implementation runs. The HWRF pre-implementation runs were dated in early April of 2014 and there are some differences between the system used then and the system we use, which dated late June in 2014. A sanity check is needed to see whether the changes made after the pre-implementation runs would alter the solutions. To do this, the DTC conducted 31 end-to-end runs for Irene, following the default configurations of the system, and then compared them to the runs from NCEP/EMC. In this study, we focus on the initialization of the HWRF model. By default, vortex initialization and data assimilation are both turned on. After initialization from the GFS (Global Forecast System, for the parent domain) and GDAS forecasts (Global Data Assimilation System, for the data assimilation domains), vortex initialization is performed to correct the storm intensity, structure and location, using either the bogus storm (for the cold start HWRF or the first cycle of the storm) or the storm from the 6-hour forecast from the previous cycle (for the storm cycled HWRF). The fields after vortex correction are then fed into the GSI hybrid data assimilation as the background for further adjustment, based on available observations.

Figure 5 shows the aggregated intensity biases for Irene from the HWRF runs at the DTC (HDTC), using the default 2014 HWRF configurations, in comparison to the HWRF pre-implementation runs from NCEP/EMC (H214). As can be seen, there are some differences between the two set of runs, with the DTC runs having slightly smaller intensity bias change but the spin down is still present and the aggregated intensity bias changed for about 10 knots in the first 12 hours. This suggested that the intensity spin down still existed in the 2014 HWRF system. Next we will mainly focus on Irene (2011) and investigate which components of the HWRF system are causing the spin down.

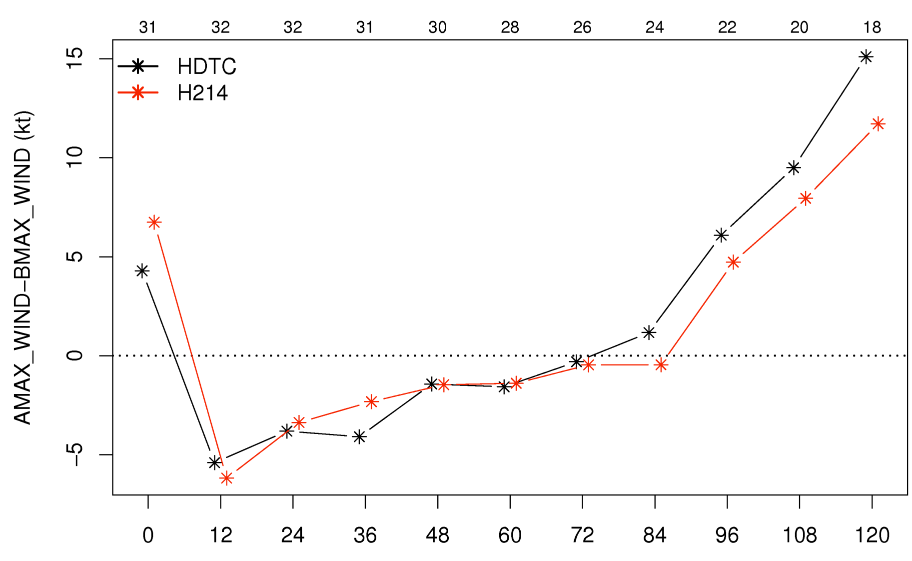

Figure 5. Aggregated intensity biases of Irene (2011) from the 2014 HWRF runs from the NCEP/EMC (red, H214) and the DTC runs following the default configurations (black, HDTC). The X-axis corresponds to the forecast hours (0-120).

Figure 6 gives the intensity forecast in the first 9 hours at 00Z August 24, 2011, based on the maximum wind speed output every 5 minutes from the 2013 (H213) and 2014 (HDTC) HWRF runs with the default configurations. The benefits of showing the wind output every 5 minutes is to avoid the possible inaccuracy of the intensity forecast in the ATCF files, which are usually based on the snapshots at specific forecast hours. The initial intensity for the 2014 HWRF run is at around 84 knots but rapidly decreases to less than 70 knots in the first 3-4 hours. This acute decrease of about 15 knots suggests that the storm structure didn't sustain long even though the initial storm is as strong as the observed, which makes it a very good case to study about the intensity spin down.

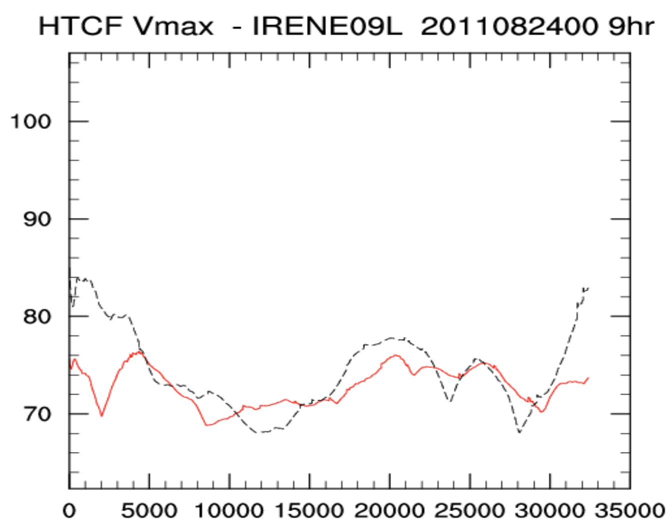

Figure 6. The intensity forecast in maximum wind speed in the first 9 hours from the 2013 (red) and 2014 (black) HWRF runs, initialized at 00Z August 24, 2011. The X-axis corresponds to the output steps for the intensity – every 5 minutes.

Another look at the intensity spin down at 00Z August 24 is to compare the 2-dimentional wind fields at the initial time (0-hour forecast) and the later times (3-hour forecast shown here), as seen in Figure 7. For both near surface (10 meter) and low-level (850hPa) fields, the wind speeds, shown in colored shadings, are reduced after 3 hours, suggesting a poorly maintained storm structure for this case.

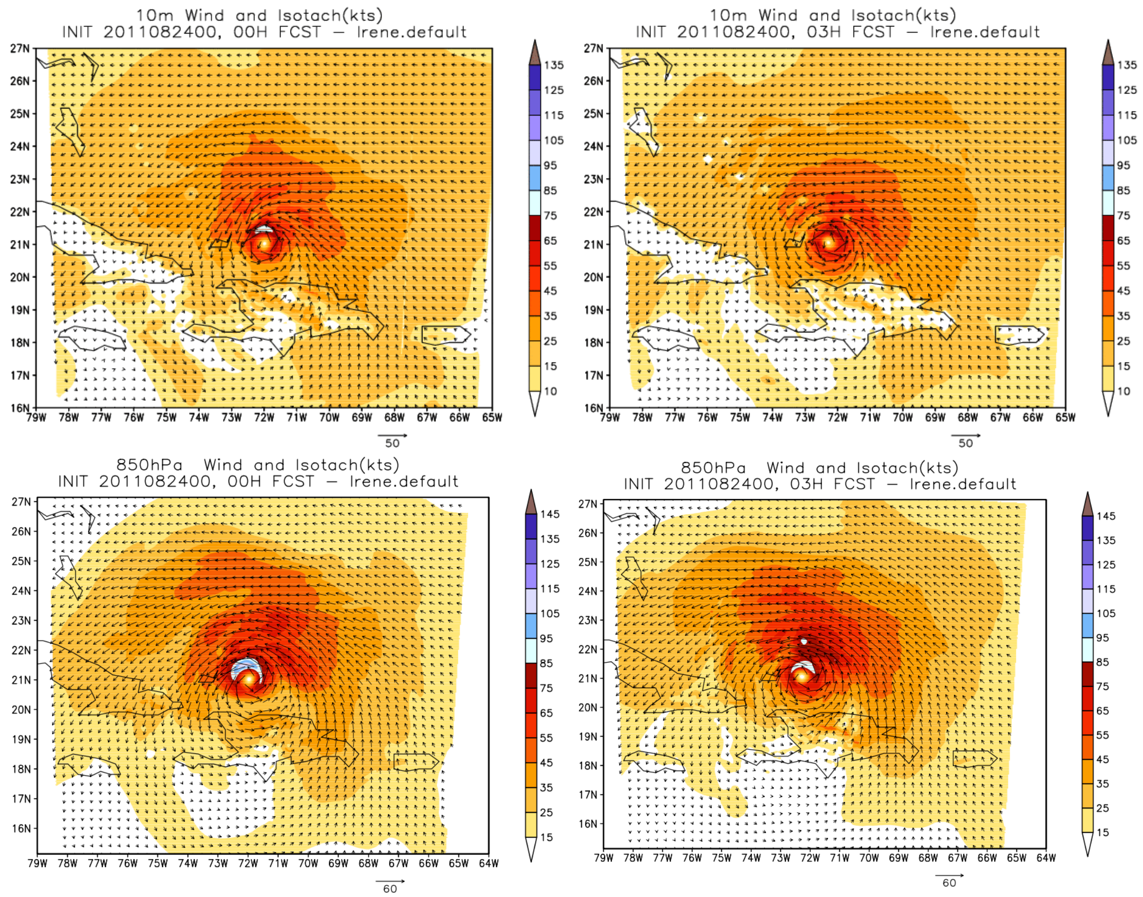

Figure 7. 10 meter (upper panel) and 850hPa (lower panels) wind vectors and isotach (knots, colored) for the 0-hour (left) and 3-hour (right) forecasts initialized at 00Z August 24, 2011.

4. Experimental design and test results

In order to find out what are causing the intensity spin down and what can be done to mitigate this problem, the DTC performed a number of experiments to examine different aspects of the system, which will be discussed in the following section.

4.1 Impact of Tail Doppler Radar data

Figure 8 shows the conventional data coverage for ghost_d03 at 00Z August 24, 2011. As can be seen, the majority of the observations are the Tail Doppler Radar

(TDR) radial wind, which are concentrated in the storm region with high temporal and spatial frequency. This leads to the question that what is the role of the TDR data assimilation? Does it help refine the storm structure by assimilating the high temporal and spatial frequency observations? Or does it degrade the storm structure and contribute to the spin down?

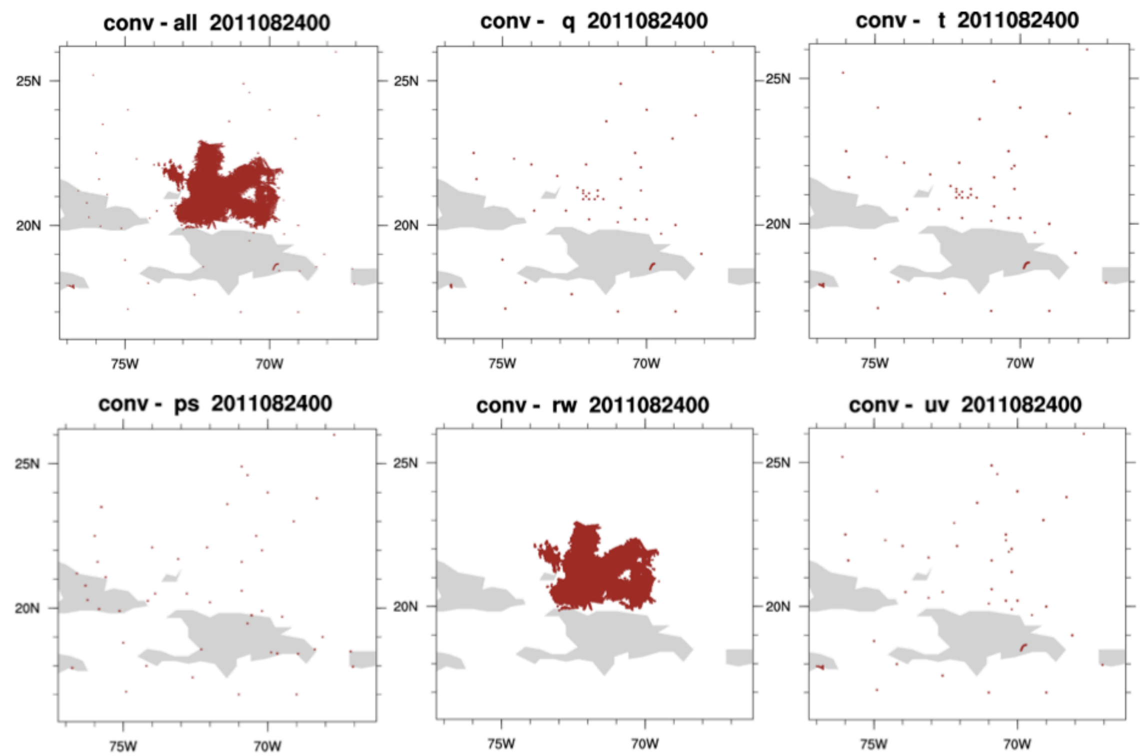

Figure 8. Data coverage of the conventional observations for ghost_d03 at 00Z August 24, 2011. All-all the conventional data; q-humidity observations; t-temperature observations; ps-surface pressure observations; rw-Tail Doppler Radar (TDR) radial wind; uv-wind observations.

To answer this question, the following experiments were conducted to isolate the impact of TDR, when the vortex initialization is turned on or off before the DA:

- HDTC: Both vortex initialization and data assimilation turned on (default 2014 HWRF setting), but TDR data were not assimilated

- HNVI: Data assimilation turned on, but no vortex initialization, TDR data were not assimilated
- TDTC: Similar to HDTC, but TDR data assimilated
- TNVI: Similar to HNVI, but TDR assimilated

Among the 33 cases that spanned from 18Z August 20 to 00Z August 29 for Irene 2011, there are only 8 dates that TDR data are available. Besides the runs with TDR assimilated, the same 8 cases were run without TDR data to form a homogeneous sample for the comparison. Figure 9 shows the comparison of the runs with or without TDR, aggregated on the 8 dates that TDR are available. It can be seen from the comparison that TDR data assimilation seems to make the spin down worse, with the 12-hour intensity bias dropped to around -8 knots, when there is vortex initialization (HDTC and TDTC). However, when looking at other forecast hours (24-120 hours), TDR assimilation largely reduced the intensity bias (TDTC). In the absence of vortex initialization, there is no intensity spin down and the TDR data assimilation greatly improves the initial intensity forecast for the first 36 hours and brings the initial intensity much closer to the observed value. Another comparison between the 8 dates that TDR are available and the 25 dates that TDR are unavailable also suggests that TDR data assimilation does help with the initial intensity forecast when the vortex initialization is turned off (not shown here).

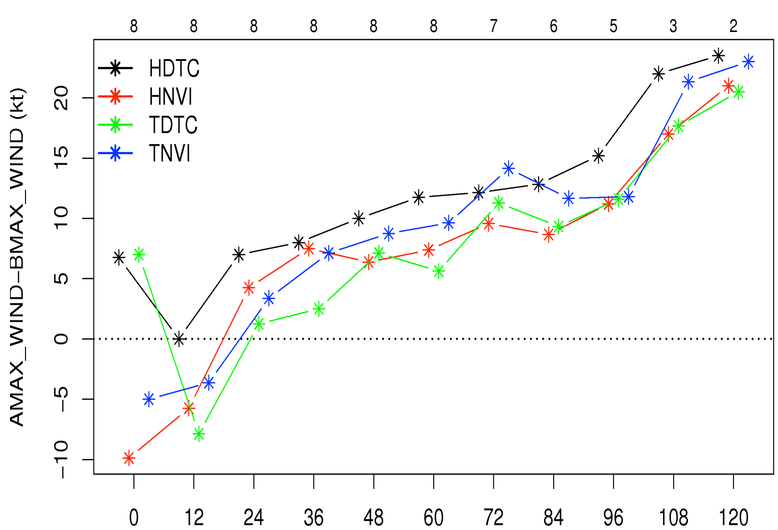

Figure 9. Aggregated intensity bias for the 8 dates with TDR available: 2011082400, 2011082412, 2011082512, 2011082518, 2011082600, 2011082612, 2011082700 and 2011082712. The X-axis corresponds to the forecast hours (0-120).

4.2 impact of DA on ghost_d02

Looking at the data assimilation configurations for the 2013 and 2014 HWRF (Table 1), one main difference is that 2014 HWRF uses GFS analysis to initialize the parent domain and the ghost_d02 domain is now one of the DA domains. And another important difference is the additional observations, including satellite radiance, satellite winds and GPS RO, assimilated in the domain ghost_d02. Would the assimilation on ghost_d02 make a huge difference and contribute to the spin down? To isolate the impact of DA on ghost_d02, 2 sets of experiments were conducted:

- HNVI: data assimilation on ghost_d02 and ghost_d03, no vortex initialization
- HNV3: similar to HNVI, but data assimilation on ghost_d03 only

The only difference between HNVI and HNV3 is whether observations were assimilated on ghost_d02. The vortex initialization is excluded here to simply examine the effect of DA. The intensity biases from the two configurations (HNVI and HNV3) are quite close, suggesting that the DA on ghost_d02 doesn't seem to make significant difference. A further examination on the intensity biases based on the 8 TDR cases (TNVI and TNV3) and 25 non-TDR cases (NNVI and NNV3) also confirms that the removal of the DA on ghost_d02 (TNV3 and NNV3) didn't change the intensity biases much when compared to TNVI and NNVI, regardless of the TDR assimilated or not (Figure 10).

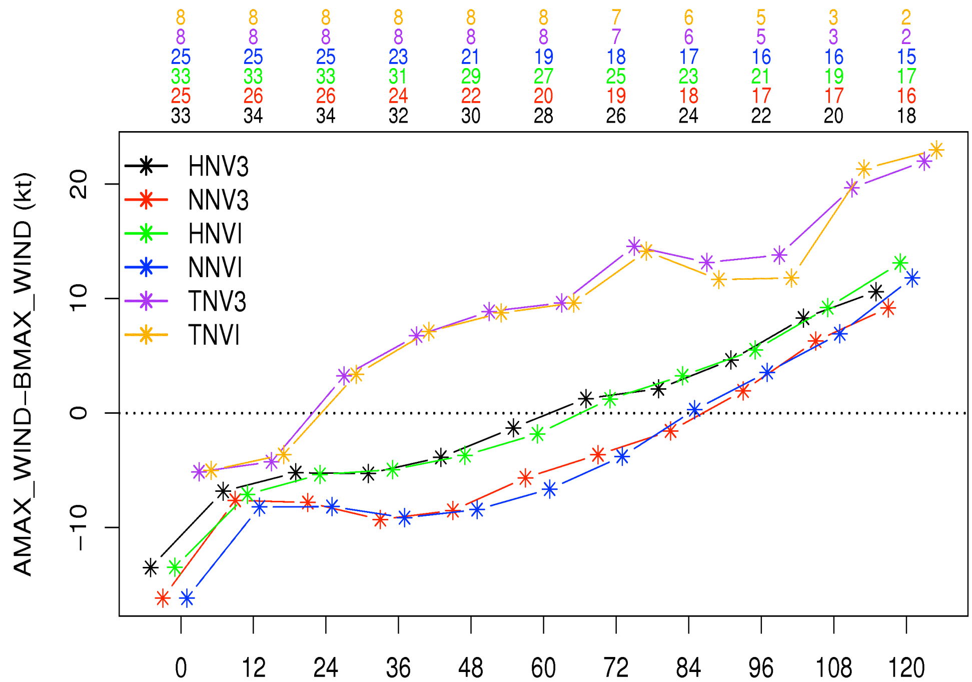

Figure 10. Aggregated intensity biases for the runs with or without DA on ghost_d02. DA on ghost_d03 only: HNV3 (all 33 cases), NNV3 (25 non-TDR cases) and TNV3 (8 TDR cases); DA on ghost_d03 and ghost_d02: HNVI (all 33 cases), NNVI (25 non-TDR cases) and TNVI (8 TDR cases). The X-axis corresponds to the forecast hours (0-120).

4.3 relative roles of vortex initialization and data assimilation

The following experiments were conducted to examine the relative roles of vortex initialization and data assimilation:

- HDTC: Both vortex initialization and data assimilation turned on (default 2014 HWRF setting)
- HGFS: Both vortex initialization and data assimilation turned off
- NGSI: Vortex initialization turned on, but no data assimilation
- HNVI: Data assimilation turned on, but no vortex initialization

Figure 11 gives the aggregated intensity biases for the above four sets of experiments. As can be seen, the initial storm intensity tends to be weaker than the observed if without vortex initialization (HGFS and HNVI). This is reasonable since the vortex initialization is designed to correct (and quite often, strengthening) the initial storm so that it will match the observed intensity better. Without the correction, the initial intensity purely comes from the large-scale fields in the GFS/GDAS, which usually presents weaker storms than the observed and therefore there is no spin down. Comparing the runs with vortex initialization but with (HDTC) and without (NGSI) data assimilation reveals that with data assimilation on top of the adjustments after vortex initialization, the HWRF runs produce stronger initial storms than the runs with only vortex initialization, although both experiments yield stronger initial storms then the observed. But the strong storms from the HDTC experiments didn't last long – the intensity bias decrease quickly to negative values in the first 12 hours, while the HWRF runs without data assimilation didn't have this intensity spin down. This leads to the hypothesis that the intensity spin down might be caused by the data assimilation or the combined impact of the vortex initialization and data assimilation.

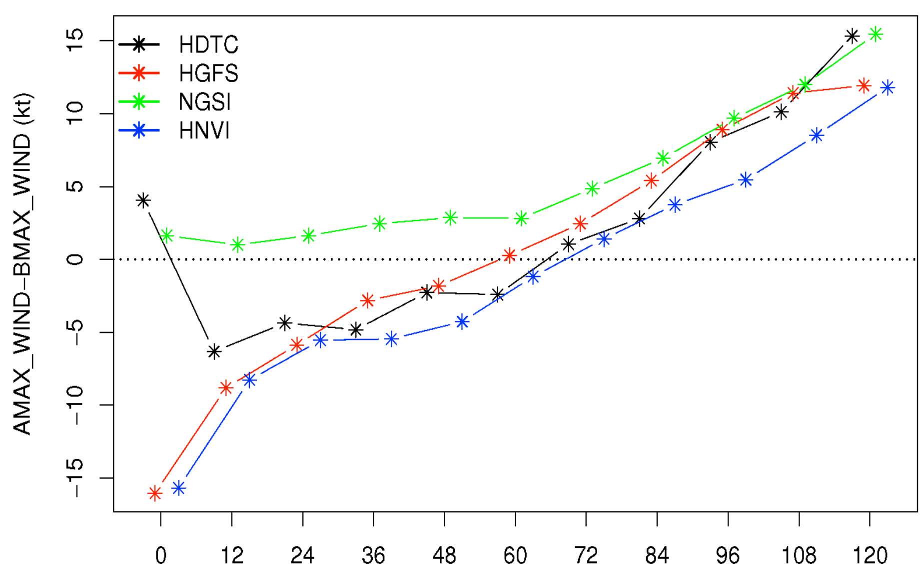

Figure 11. Aggregated intensity biases of Irene (2011) from the four sets of 2014 HWRF runs: HDTC (black), HGFS (red), NGSI (green) and HNVI (blue). The X-axis corresponds to the forecast hours (0-120).

Based on Figure 6, 00Z August 24 in 2011 was chosen to further investigate the roles of the vortex initialization and data assimilation. Figure 12 examines the fields of temperature, humidity and winds at model level 21 before and after vortex initialization and data assimilation, from the 2014 HWRF run following the default configuration. The leftmost columns are the fields before vortex initialization, in other words, from the GDAS forecast. The storm structure is relatively loose and smooth. For this case – 00Z August 24, 2011, the 6-hour forecast from the previous HWRF run (18Z August 23, 2011) was used in the vortex initialization to replace the large-scale GDAS vortex. Then the vortex was further adjusted based on the TC Vital (Tropical Cyclone Vital Statistics Records). Besides the storm relocation, the size and three-dimensional structure of the adjusted storm were modified based on the observed parameters in TC Vital, including Radius of Maximum Wind (RMW), radius of 34-kt winds (R34) and/or Radius of Outermost Closed Isobar (ROCI), maximum sustained 10-m winds (intensity) and minimum mean sea-level pressure (MSLP). As can be seen in the figure, the previously relatively loose and smooth structure was modified to be concentrated around the storm, with more small-scale structures. A well-defined closed structure is present in the wind fields, with increased temperature and humidity in the storm center. The modified fields, shown in the middle column in Figure 12, were then used as the GSI background. In this case, the TDR data, together with other observations, were assimilated to further adjust the fields. The rightmost column of Figure 12 shows the temperature, humidity and wind fields after the GSI hybrid data assimilation. Interestingly, the temperature and humidity at the storm center were reduced after the data assimilation, while the wind fields were intensified.

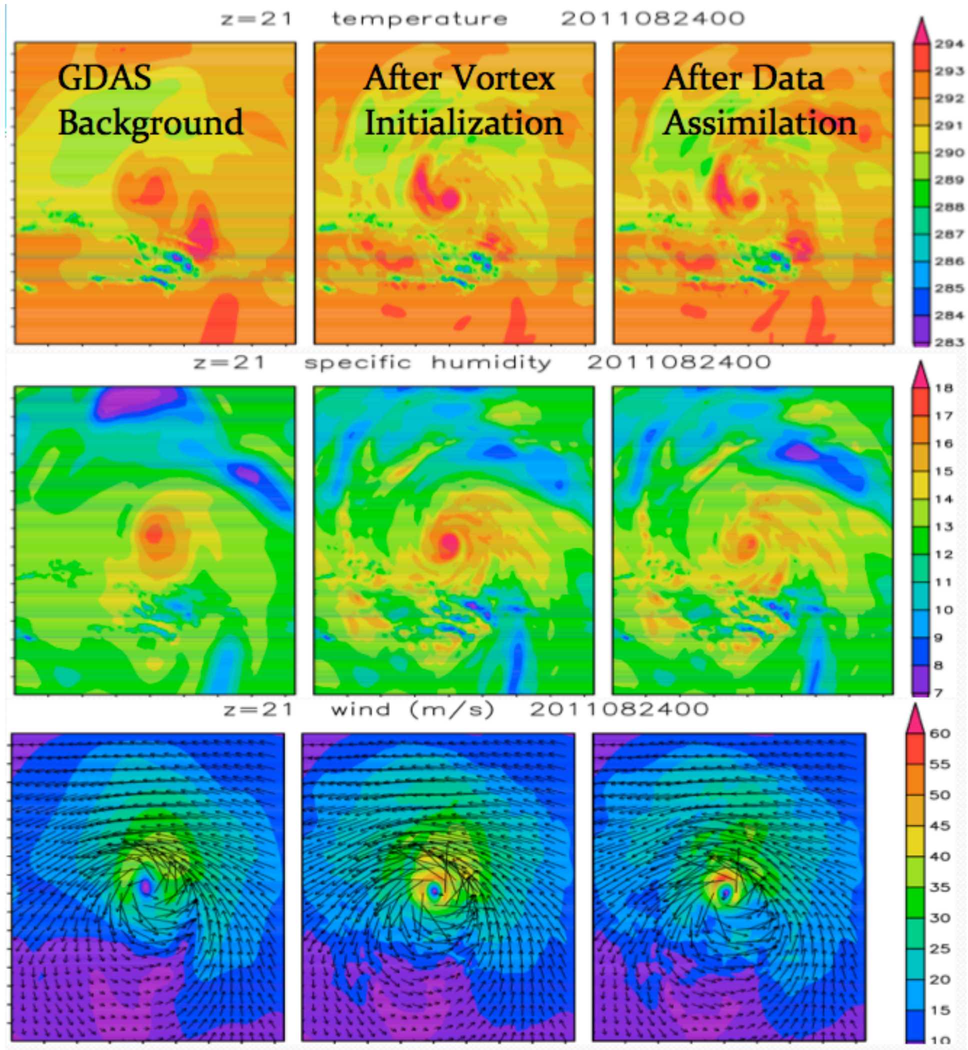

Figure 12. The temperature (top panel, in K), humidity (middle panel, in g/kg) and the wind (bottom panel, vectors and wind speed in m/s in colors) fields at model level 21 at 00Z August 24, 2011. The leftmost columns are the fields before the vortex initialization. The middle columns are after the vortex initialization. The rightmost columns are the fields after the GSI hybrid data assimilation.

Figure 13 gives the TDR radial wind at 00Z August 24, 2011 for four different levels. Notice the coloring schemes are different for the four levels, illustrated at the bottom of each plot. The observed storm location is shown in the circles and they are in good agreement with the minimum radial winds, suggesting there is no concerning displacement of the storm location. The maximum value of the radial winds are annotated on top of each plot, showing the maximum radial wind for the whole atmosphere is 53.6m/s and it is between 800mb and 700mb. For comparison to the observed in TC Vital, the near surface (100-900mb) radial winds presented a maximum at 49.5 m/s, which is still larger than that in the TC Vital (41 m/s) and the best track (80 knots, or, ~41 m/s). Since the GSI uses the background fields after vortex initialization, the maximum wind of the storm is supposed to be close to 41 m/s. Assimilation of the TDR radial winds with a maximum of around 49.5 m/s at near surface produces the GSI wind analysis that is between the GSI background and the TDR observations and therefore intensified the storm wind fields, as seen in Figure 12. On the other hand, the humidity fields, due to very limited or poor humidity observations, didn't keep up with the wind fields and were reduced after the GSI hybrid analysis, as shown in Figure 12. The inconsistent increments between the wind fields and the mass fields suggest a stronger convergent circulation coupled with less humidity supply, which is detrimental to the sustainability of the storm structure and might contribute to the intensity spin down.

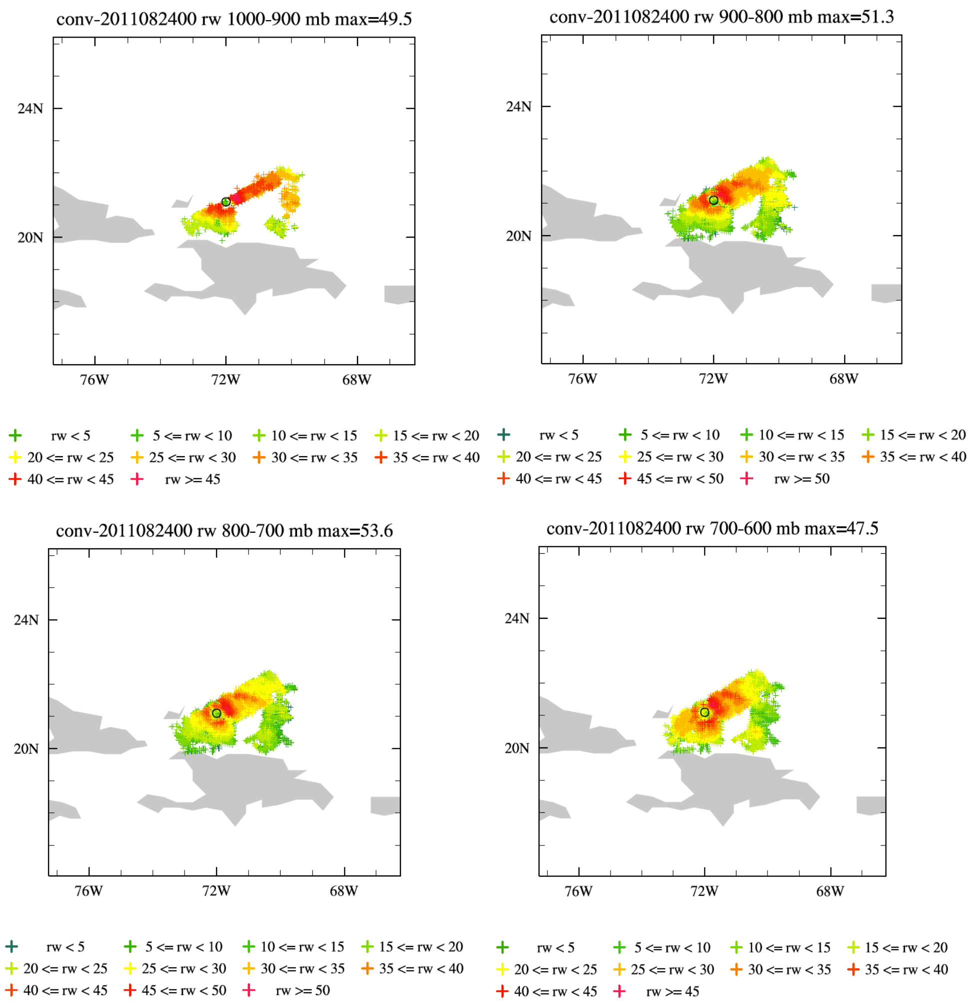

Figure 13. TDR radial winds at 00Z August 24, 2011 for the levels 1000-900mb, 900-800mb, 800-700mb and 700-600mb, as annotated on top of each panel. The circles correspond to the observed storm location. The colors give the magnitude of the radial winds, with the maximum for each level annotated on top of each panel.

In order to have a sustainable storm structure after the data assimilation, the GSI analysis, especially the mass fields, needs to be improved. There are several possible pathways to achieve this. One is to have more high quality humidity observations, together with abundant wind observations, so as to provide a more realistic wind and mass fields. Efforts can also be invested in improving the data assimilation of the TDR radial winds. This might involve improved quality control of the data and the covariance between the wind fields and mass fields such as the humidity. The hybrid variational-ensemble method is utilized in the data assimilation to incorporate flow dependent information in addition to the static background error (BE) covariance. For the static BE part, the global background error statistics, computed using the forecasts from the GFS model at NCEP, is used. A regional BE statistics, with hydrometeor variables involved and calculated for the current model, might help build a more reasonable relationship between the wind fields and mass fields. The contribution of the ensemble background errors is set to be 80% and therefore the improvement to this part will potentially benefit the TDR assimilation. The introduction of the ensemble is supposed to bring flow-dependent features and provide a better relationship between the fields. However, based on Figure 12, the relationship between the wind and mass fields were not properly presented. Note the ensemble used in the 2014 HWRF is from the GFS, with a horizontal resolution at around 50km. Therefore the ensemble covariance between the variables are based on the coarse-resolution GFS and it couldn't depict the proper relation among the regional fields at 9 and 3-km, especially for the tropical cyclones. This brings up the need for the regional high-resolution ensemble, which might present a more reasonable covariance between the different variables and contribute to the inner core data assimilation. On the other hand, a careful examination on how the GSI utilize the ensemble information might also help improve the TDR assimilation.

4.4 GSI internal imbalance

As shown in the above section, the increments from the wind and humidity fields are not consistent and this leads to strengthened circulation but with reduced humidity supply. The imbalance between the wind and mass fields doesn't support the maintenance of the storm structure, not to mention continued development of the storm as observed.

Figure 14 shows the model noise at the inner nest (d3) for the first 6 hours, initialized at 00Z August 24, 2011, for the three different HWRF configurations:

- HDTC: 2014 HWRF default configuration, vortex initialization and GSI both included
- NGSI: vortex initialization included, but no GSI
- HNVI: GSI data assimilation included, but no vortex initialization

Apparently the main difference exists between the runs with the GSI data assimilation (HDTC and HNVI) and the run without GSI (NGSI), with the latter showing much smaller initial model noise and therefore requiring less time to re-adjust the model fields to a relatively balanced state. On the other hand, the two configurations with GSI included, due to the initial imbalance in the model fields, present significant model noises at the initial time and therefore the model needs more time to adjust prior to the storm development.

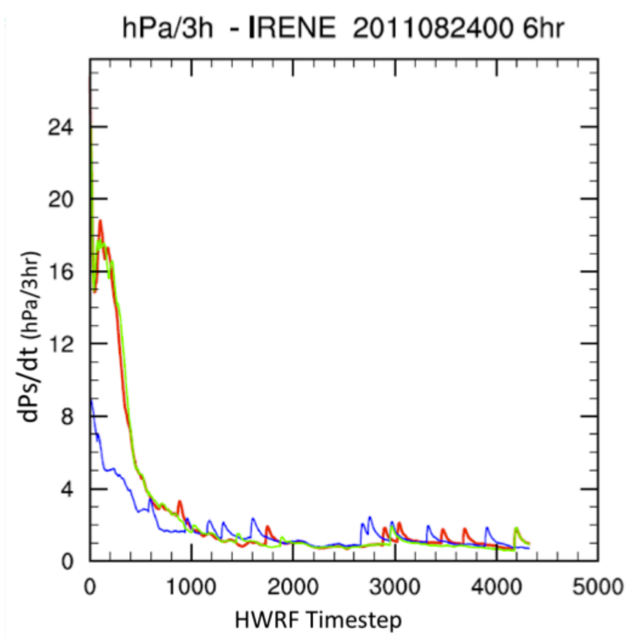

Figure 14. Model noise at the inner nest (d03) for the first 6 hours, initialized at 00Z August 24, 2011, for the three different HWRF configurations: HDTC (red), NGSI (blue) and HNVI (green). The x-axis corresponds to the HWRF model steps. The y-axis corresponds to the tendency of the surface pressure in hPa/3hr.

Figure 15 is similar to Figure 14, but gives the model noise in the first 2 hours from the run with GSI 3DVAR (red) and the run with pure ensemble contributions (blue). It can be seen that the initial model noise from the run with pure ensemble is much larger than that with GSI 3DVAR. This is reasonable in the sense that in GSI 3DVAR, the static background error statistics were applied, which comes with some dynamic constraints between the variables. On the other hand, when pure ensemble is used in the GSI, there is no such constraint available and the relationships among the different fields come from the ensemble only. This calls for some kind of constraints to be applied on the model initial fields, especially for the finer scale structures introduced through the ensemble covariance.

The DTC tried to take advantage of the dynamic constraints in the GSI system to reduce the model noise by smoothing out the gravity waves from the GSI analysis field. Also included in Figure 15 is the model noise evolution in the first 2 hours for the GSI 3DVAR run with the dynamic constraints applied, as shown in purple curve. It can be seen that applying the constraints in the GSI 3DVAR did reduce the initial model noise. Efforts were also invested to apply the constraints to the ensemble part or the total contribution (3DVAR + Ensemble) but the constraints in the GSI system doesn't seem to work properly for the regional applications. Additional work is needed to make the GSI code work and then hopefully contribute to the mitigation of the intensity spin down, without degrading the overall storm track and intensity forecasts.

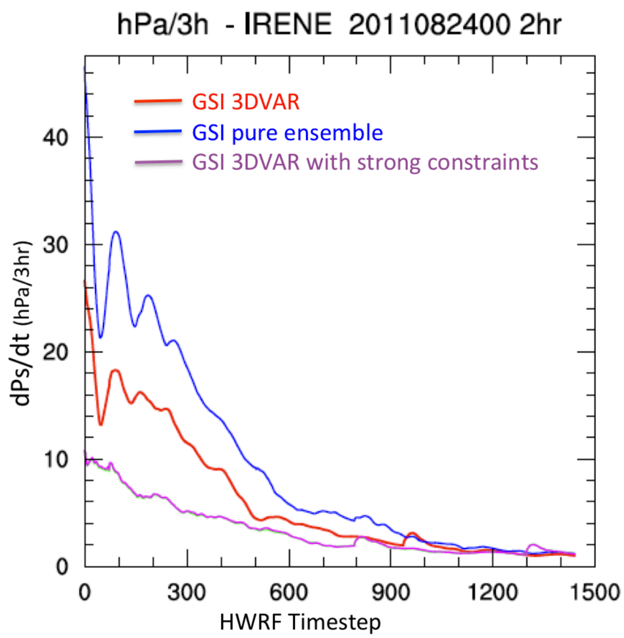

Figure 15. Model noise at the inner nest (d03) for the first 2 hours, initialized at 00Z August 24, 2011, for the three different HWRF configurations: GSI 3DVAR (red), GSI pure ensemble (blue) and GSI 3DVAR with constraints (purple). The x-axis corresponds to the HWRF model steps. The y-axis corresponds to the tendency of the surface pressure in hPa/3hr.

4.5 Impact of regional high-resolution ensemble

As discussed in Section 4.3, the coarse-resolution GFS ensemble used in the 2014 HWRF might not properly represent the flow-dependent information in the high-resolution regional HWRF model fields. This section presents the work that applied regional high-resolution ensemble in the hybrid data assimilation, in place of the GFS ensemble.

Due to the lack of the regional ensemble for Irene (2011), a different tropical cyclone, Edouard (2014), is selected, mainly because of the availability of the regional 9-km ensemble data kindly provided by Henry R. Winterbottom at NOAA/ESRL/PSD. Edouard was the 6th named storm in 2014 in the Atlantic and remained in the open Atlantic Ocean during its lifetime from 11 to 19 September (Figure 16).

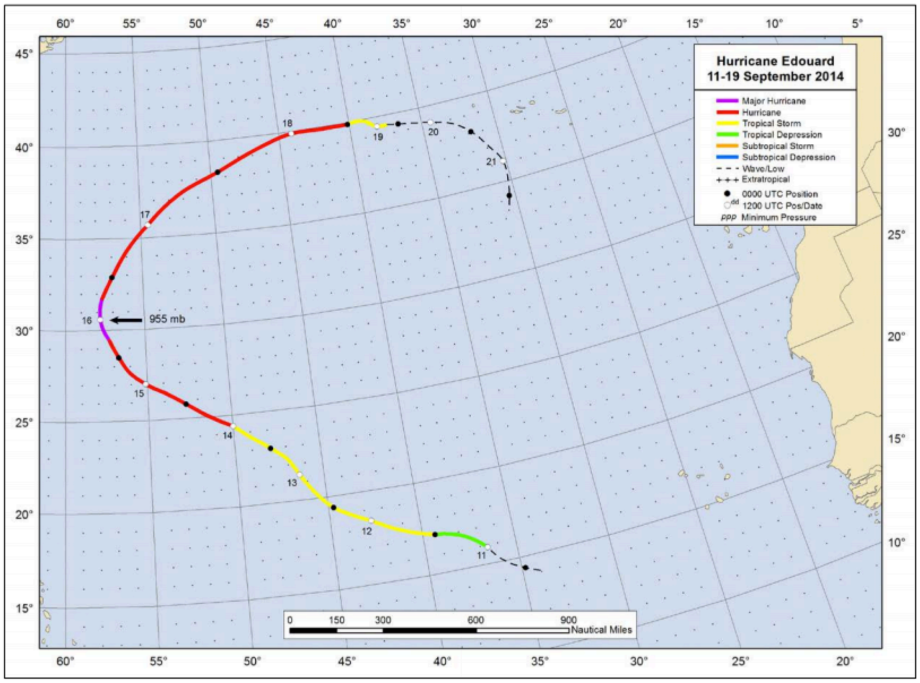

Figure 16. Best track positions for Hurricane Edouard, 11-19 September 2014.Adopted from the NHC tropical cyclone report for Hurricane Edouard (http://www.nhc.noaa.gov/data/tcr/AL062014_Edouard.pdf).

The DTC conducted 30 runs for Edouard (2014) following the default 2014 HWRF configurations. Figure 17 shows the aggregated intensity biases, in which the intensity bias dropped rapidly from positive to negative in the first few hours, and hence making it another good case for studying the spin down.

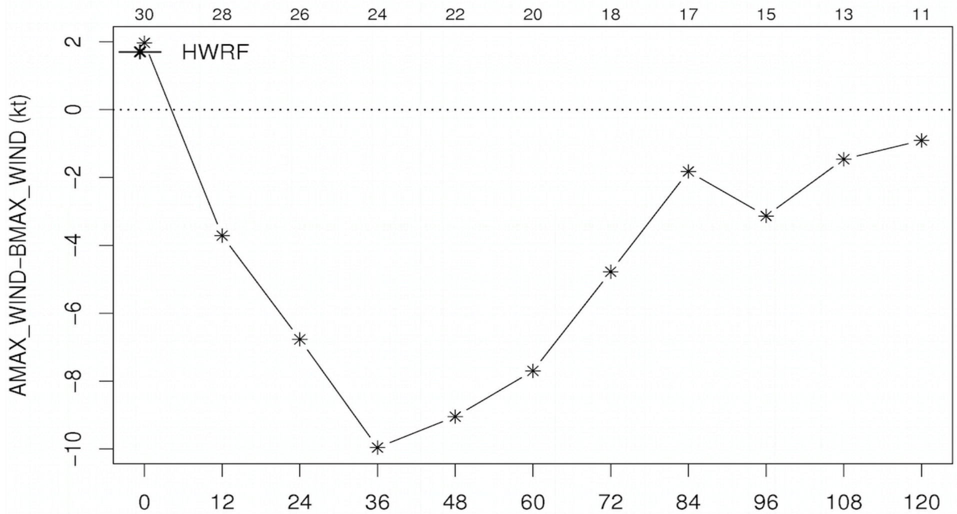

Figure 17. Intensity bias of Edouard (2014) from the 2014 HWRF runs. The numbers of cases are shown on top of the plots. The X-axis corresponds to the forecast hours (0-120).

In addition to the default 2014 HWRF runs, additional experiments are conducted, with the 80-member HWRF regional ensemble of horizontal resolution of 9km applied in the GSI hybrid on ghost_d03. The regional ensemble was not applied in ghost_d02, mainly due to the limited domain size of the ensemble. This practice is ok based on the discussions in section 4.2, which suggested the data assimilation on ghost_d02 is not crucial. The introduction of regional 9-km ensemble is expected to improve the tropical cyclone forecast, which is confirmed in Figure 18. It can be seen that in the initial hours, the sharp decrease of storm intensity from the run with GFS ensemble (blue curve) was greatly improved in the run with the high-resolution regional ensemble (black curve). More extensive tests might help further confirm the benefits of applying high-resolution regional ensemble.

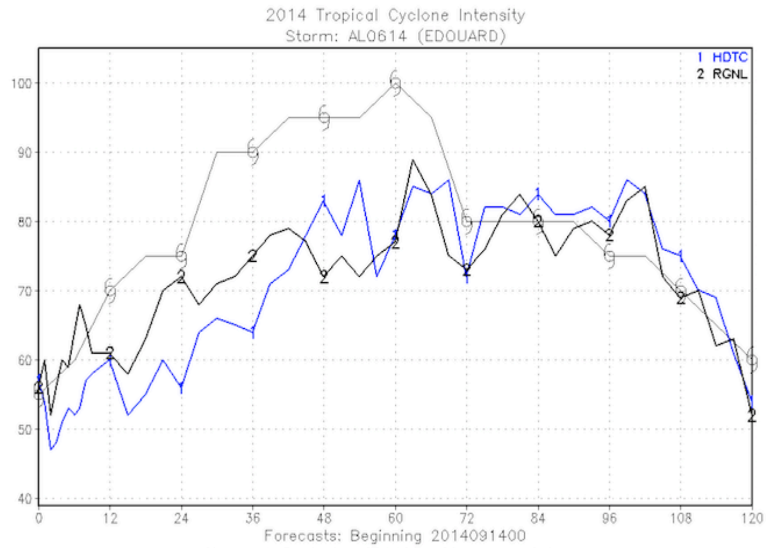

Figure 18. Intensity forecast of Edouard at 00Z September 14, 2014. The blue curve corresponds to the default 2014 HWRF run with the GFS ensemble; the black curve corresponds to the 2014 HWRF run with the 9-km regional ensemble on ghost_d03. The grey curve is the observed intensity from the best track.

5. Discussion

In collaboration with research and operational centers, the Developmental Testbed Center (DTC) works toward the improvement of Data Assimilation and initialization of numerical models for tropical cyclone forecasting. This report covers recent work performed in the framework of the 2014 operational HWRF model, which applied some critical updates to various aspects of the system from the 2013 HWRF system, including, but not limited to, the upgraded vortex initialization scheme and some important changes to the hybrid variational-ensemble configuration of the GSI system. The data assimilation is now performed for the two new intermediate domains (ghost_d02 and ghost_d03, with 9km and 3km horizontal resolutions respectively), with more observational data (satellite radiance, satellite derived winds, GPS RO, etc) in addition to the conventional observation and the TDR data.

Based on diagnostics of the tropical storm intensity forecasts from the NCEP/EMC 2014

HWRF pre-implementation runs, cases have been selected and multiple runs have been conducted, with the main focus on tackling the tropical storm intensity spin-down issues within the 2014 HWRF runs, which corresponds to the intensity forecasts changing rapidly from too strong to too weak compared to the observed at the initial forecast hours. The extensive investigations covered the following aspects:

- Impact of the DA on ghost_d02, which turns out to be less important and therefore possibly not a contributing factor to the spin down.
- Impact of the TDR data assimilation, which improves the intensity forecast at the absence of the vortex initialization; However, when there is vortex initialization performed before the data assimilation, the additional information from the TDR tends to contribute to spin down.
- The relative roles of the vortex initialization and the GSI hybrid data assimilation, which suggested that performing data assimilation on top of the vortex initialization contributes to the intensity spin down. More detailed diagnostics on a case with TDR available (00Z August 24, 2011) suggested that the additional information from the TDR assimilation on top of the vortex initialization produces a strengthened wind circulation but with less humidity supply, causing the unbalanced model fields and poorly maintained storm structure. Additional high-quality moisture observations might help fix the problem. On the other hand, better assimilation of the TDR wind observations might also help mitigate the intensity spin down. This can be achieved by either better quality control of the observations or improved data assimilation through applying high-resolution regional ensemble.
- GSI internal imbalance, which shows that the initial model noise tends to be larger when there is GSI included. And the model noise from the ensemble contribution exceeds that from the 3DVAR part. Applying dynamic constraints to the 3DVAR runs yields reduced model noise. Additional work is needed on applying the constraints to the ensemble part or the total contribution from the 3DVAR and ensemble parts.
- Impact of applying regional high-resolution ensemble, which shows that replacing

the coarse-resolution GFS ensemble with the high-resolution regional ensemble in the GSI hybrid helps with the initial intensity forecasts.

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